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Rock-magnetic and Paleomagnetic Studies on Sediment Cores from Lake Baikal

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I. Introduction

Lake Baikal is an important and unique site for paleoclimate studies because of its high-latitude, continental-interior setting, and its long, continuous stratigraphic record. The Baikal Drilling Project that is an international research project was initiated on 1992 to investigate the paleoclimatic history and tectonic evolution of Lake Baikal sedimentary basin. Fig. 1 shows the drilling sites on 1993-1999. These sites were widely located in Lake Baikal; Buguldeica saddle (BDP-93), Academician ridge (BDP-96, BDP-98) and Posolskaya bank (BDP-99).

Dating is essential for the environmental research using lake sediments. In many kinds of dating methods for sediment, paleomagnetic method that utilizing geomagnetic record retained by magnetic minerals in the sediments is the one of useful methods. Paleomagnetic method is efficiently used to date sediments from Lake Baikal. Especially for BDP-96 cores from Academician ridge, showed apparent normal-reverse pattern of geomagnetic polarity, the time scale of the cores was established based on magnetostratigraphy (Sakai et al., 2000; Sakai et al., 2003).

Firstly, this text deals basic methods for paleomagnetic dating and rock-magnetic study. Rock-magnetic study that analyzes the magnetic properties in the sediments, can be used to investigate climate and environmental change as well as to confirm the reliability of the magnetization in sediments. Among of the many parameters of magnetic properties, magnetic susceptibility is frequently used because of the rapid and non-destructive measurement using the bulk sample, and susceptibility measurement is also used on the whole core.

Secondary, this text introduces the practical examples for the dating sediments by magnetostratigraphy and also the paleoenvironmental study by rock-magnetism on Lake Baikal.

II. Fluctuation of Geomagnetic Field

The Earth consists of the crust, mantle and core; further the core is divided into liquid outer core and solid inner core. Spherical harmonic analysis show that the geomagnetic field is mainly dipole magnetic field possibly generated by the outer core current. As the general representation, the geomagnetic field is approximated by magnetic field of bar magnet at the geocentric position. As shown in Fig. 2, in the polarity of the bar magnet at present, geographical North Pole is S-pole of the magnet and geographical South Pole is N-pole of the magnet. Magnetic field line drawn by the Earth magnet is spreading into cosmic space and the shape is pressed by solar wind at sun side and flows to the counter direction. Thus, Earth's magnetosphere that is outermost Earth and affects on the global environment, changes reflecting the inner state of active Earth.

We can express in three components geomagnetic field that we can observe on the ground (Fig. 3). Usually, in discipline of geomagnetism, declination from geographical North, inclination from horizontal plane and intensity of total magnetic force are used as the three components.

Although observational data of geomagnetic field cover only past 100 years, geomagnetic history go back to the older age as soil and rocks record geomagnetic field at the time when they are formed ("geomagnetic fossil").

Fig. 4 shows the changes in the components of geomagnetic field (declination, inclination, total intensity) during the past 2000 years. Variation of the geomagnetic field with longer time period from generally 102 years is called as the secular variation. Further, as the more significant geomagnetic phenomena, the reversals of geomagnetic field; i.e. geomagnetic polarity switch position each other have been occurred at a frequency of c.a. 200000 years.

III. Paleomagnetism, Rock-magnetism of Sediments

Rocks and sediments generally contain iron oxide minerals such as Fe_3O_4, Fe_2O_3. They are called magnetic minerals because they can acquire the remanent magnetization. The magnetic minerals in such the natural materials could record the past geomagnetic field; its declination, inclination and field intensity.

In the case of sediments deposited in the water condition, the magnetic minerals tend to align their magnetic vector toward the geomagnetic field in their deposition process. Therefore, the magnetic minerals in lake and sea floor sediments, statistically aligned their magnetic vector to geomagnetic direction at the age of deposition. Magnetization that acquired by this mechanism is called as the depositional remanent magnetization (DRM). The DRM of sediment sequence or sediment core is regarded as the successive fossil of geomagnetic field during the deposition process (Fig. 5). Directions for DRM of sediment sequence or sediment core might show the polarity changes (normal-reverse of polarity pattern) if they have enough long record that it experienced some geomagnetic reversals.

Magnetostratigraphy

Normal-reverse polarity pattern of magnetization of sediments can be used dating of the sediment. Many measurements of direction of magnetization for sediments and rocks of terrestrial, lacustrine and marine origin in various ages had been associated with biostratigraphy and radioisotope age and by which the geomagnetic polarity time scale (GPTS) had been made. Date drawn by paleomangetic method comparing the measurements of magnetization for the sediments sequence of core under the study with GPTS is called magnetostratigraphy.

Recently, the GPTS was tuned by comparison with $\delta^{18}O$ curve and solar isolation curve (Cande and Kent, 1995) is commonly used (Fig. 6). Geomagnetic reversal is global event which coincidentally occurred while changes in biota have regional difference. Therefore magnetostratigraphy has advantage on the synchronism between the data obtained from different areas as compared to biostratigraphy based on changes in biota.

Magnetic properties

Magnetic property such as magnetic susceptibility which depend on mineralogy, grain size and content of magnetic mineral in the sample, not depend on past geomagnetic field, that is physical parameter. In hemipelagic sediment, it is known that changes in magnetic properties for sediments reflect paleoclimatic change (Kent 1982). Content of magnetic mineral in sediment reflect the contribution of terrigenous material (Bloemendal and deMenocal, 1989). In hemiplagic sediment, magnetic susceptibility is generally low in an interglacial period and high in a glacial period (e.g. Kent, 1982; Robinson, 1986). This phenomenon is thought to reflect the dilution and concentration of magnetic material due to a change in biogenic accumulation, such as carbonate, with climatic change (Kent, 1982). In hemipelagic sediment, terrigenous material can be regards as relatively constant while in lacustrine settings, however, the effect of fluvial activity and turbidity current must be taken into account. Magnetic properties of lake sediments may respond to climatic change differently from in marine sediments. Therefore, reliable age scaling is necessary to discuss connection between magnetic properties of the sediments and climatic change. In the vast lake such as Lake Baikal, the areas like hemipelagic environment can exist. In Lake Baikal, diatom ooze is dominant as biogenic component in the sediments (Cater and Colman, 1994), dilution of terrigenous material by diatom ooze can change magnetic properties of sediments. In paleoenvironmental and paleoclimatic study, the methods using magnetic properties sediment has advantages that the measurement is rapid and non-destructive. Analytical method of utilizing the magnetic properties is called also rock-magnetism. It is used in diagnosis for stability of remanent magnetization of paleomagnetic as well as in these environmental approaches.

IV. Sampling and Experimental Procedure

In pleomagnetic study on BDP cores, the discrete samples were taken from half core sections divided into every 1 m. Sampling intervals range 1-20 cm according to desired resolution of geomagnetic change. 5-cm^3, 8-cm^3 or 10-cm^3 plastic boxes were used in the sampling for paleomagnetic and rock-magnetic study (Fig. 7).

X, Y, Z components of natural remanent magnetization (NRM) on collected samples were measured and declination, inclination, intensity of magnetization vector were calculated by the measurement. Pass though type cryogenic magnetometer 760-3.2 LC (2G Enterprises) is frequently used in paleomangetic study on BDP. In drilling cores, due to the rotation during boring, declination data of the core are generally useless, usually only inclination data are available for paleomagnetic study. Sometimes relative change in declination is used. Because Lake Baikal lies at high latitude, the magnetization of the sediments shows deep inclination. We can clearly distinct normal and reverse of geomagnetic polarity on the magnetization of the sediments.

To use magnetization of sediments for paleomagnetic dating, reliable magnetization maintains information of geomagnetic field at the time when the sediments deposited. The secondary magnetization is sometimes overprinted later on over long time. To elucidate the original magnetization by eliminating the secondary magnetization, demagnetization experiment is conducted by the alternating magnetic field method. Usually alternating magnetic field apply to the sample is raised stepwise. Remanet magnetization is measured after each demagnetization step. Zijderveld diagram (Zijderveld, 1967) in Fig. 8 is used to analyze the change in direction and intensity of magnetization vector by the demagnetization. In this diagram, the magnetization vector is decomposed to vertical and horizontal components, then both the components are projected together. Here, the horizontal magnetization component (projcction to North-South - East-West plane) is represented by filled circle, while the vertical component (projection to North-South - Up-Down plane) is shown by an open circle.

In the case of large sample number, after measuring of NRM (natural remanet magnetization), pilot samples are chosen for a stepwise alternating field (AF) demagnetization experiment. Diagonal vector analysis (Zijderveld, 1967) is used for the pilot samples to determine the minimum demagnetizing field that can avoid secondary magnetization. The remaining samples are then demagnetized at the field.

On BDP, after measuring NRM, one pilot sample was selected every 2 m and then stepwise alternating field demagnetization was performed in 5 mT steps in range 5-80 mT. Because demagnetization at 10-20 mT is enough to eliminate the secondary magnetization in pilot samples, demagnetizations at 5, 10, 15 and 20 mT were applied on the remaining samples. In samples of BDP-96 and BDP-96 cores, magnetizations after 15 mT demagnetization were used as paleomagnetic data. Apparatus of alternating field demagnetization is attached to the pass-through type cryogenic magnetometer 760-3.2 LC (2G Enterprises) (Fig. 9).

Here are descriptions of rock-magnetic parameters (magnetic properties).

Magnetic susceptibility (κ) is the characteristic of the capacity of magnetization in the sample. It is studied by the measurement of induced magnetization (J) under the artificial magnetic field (H); the relation is expressed as $J=\kappa H$. In rock-magnetic study, usually primary magnetic susceptibility induced by relative low magnetic field of 0.08 mT. Magnetic susceptibility is sensitive to concentration of magnetic mineral in sediment and is often used as the parameter reflects paleoclimatic change.

ARM (anhysteretic remanent magnetization) is an artificial magnetization acquired under the combination of an alternating magnetic field of 0.8-0.1 mT and a week direct field of 0.05-0.08 mT. Mechanism for acquiring ARM is that the magnetic components that is perturbed by alternating field, align their magnetic vector with direction of the direct field, thus magnetization is acquired. ARM is often used in calculation of relative geomagnetic field intensity from lake and sea floor sediments.

IRM (Isothermal remanent magnetization) is imparted at a strong direct magnetic field (0.1-3T) by electromagnet. Magnetization of almost natural material reaches saturation by magnetic field of 1T and therefore magnetization that is imparted at 1 T is defined as the saturation IRM (SIRM) in rock-magnetic study.

V. Paleomagnetic and Rock-magnetic Studies on Lake Baikal Sediments

Here, the examples of paleomagnetic study on BDP cores are introduced.

5-1. Paleomagnetic study of sediment cores from Academician Ridge

Academician ridge, a structural and bathometric high between the northern and central basin, is isolated from direct fluvial and downslope sedimentation. Colman et al. (1993) assessed the sedimentation rate of this area (0.03 mm/yr in Holocene) is lowest in Lake Baikal from the dating the surface sediment. Because little influence of direct fluvial and turbidity current, stable, homogenous and consecutive paleoenvironmental record are expected in this area.

In 1996, BDP-96-1 and 96-2 sediments cores (53° 41'48"N, 108° 21'06"E) and in 1998, BDP-98(53° 44'48"N, 108° 24'31"E) sediment cores were drilled at Academician Ridge (Fig. 1). Lengths of the obtained cores are 200 m (BDP-96-1), 100 m (BDP-96-2) and 600 m

(BDP-98), respectively. BDP-98 core is divided into the upper 200 m part (BDP-98-1) and lower 400m part (BDP-98-2). Lithofacies for these cores is blue-gray clay to brownish silt and alternate diatom-rich layer and no-diatom layer.

In samples of BDP-96 and BDP-98 cores, the magnetization after 15 mT alternating field demagnetization that is enough to eliminate the secondary magnetization were used as paleomagnetic data. Fig. 10 shows the changes in declination, inclination and intensity of magnetization vector with depth from the discrete samples of BDP-98, where the clear polarity reversal pattern identified.

Fig. 11 shows comparison of polarity changes in inclinations of BDP-96 and BDP-98 with geomagnetic polarity time scale (Kande and Kent, 1995). The polarity reversal pattern of each core shows good correlation. BDP-96-2 covers c.a. 2500 kyr from Brunhes normal Chron to Matuyama reversed Chron, and BDP-96-1 and BDP-98-1 elongate to c.a. 5000 kyr including further older periods; Gauss normal Chron and Gilbert reversed Chron. Fig. 12 shows the correlation between depth and age for the assigned geomagnetic polarity boundary in Fig. 11. Through the linear relation in the figure, we can estimate the average sedimentation rate as about 4.0cm/kyr. As sedimentation from the slop of the line as shown in Fig. 11 is stable in 5000 kyr, it suggests that the sedimentation at Academician Ridge has not suffered large disturbances such as long hiatus or very large turbidity current during the past 5000-kyr.

There is long reversed polarity region of 290-350 m for BDP-98-2. Interpretation of this region is argued between the researchers. Using the correlation as shown in Fig. 11, it suggests extremely high sedimentation rate compared to usual sedimentation rate on this area that reflects the something significant environmental change (Sakai et al., 2003).

5-2. Fluctuation in magnetic susceptibility of sediment cores from Academician Ridge

In Lake Baikal, diatom-rich sediments reflect warm environment (Shimaraev et al., 1992). On short cores of ~10 m length from Academician ridge, the susceptibility showed high value during glacial periods and low value during interglacial periods, whereas biogenic silica content was high during interglacials and was low during glacials (Sakai et al., 1997). In addition, as the magnetic susceptibility is sensitive to terrigenous material, it may take the increase of ice rafted sand and aeolian dust. Rapid and non-destructive measurement of magnetic susceptibility as well as diatom or biogenic silica can be utilized in the paleoenvironmental and paleoclimatic research around Lake Baikal.

Fig. 13 shows the variation of susceptibility with time of BDP-96-2 and BDP-98 cores. In upper parts of cores, changes in magnetic susceptibility show good correlation. As BDP-96-1 core poorly recover in the layer older than 3 Ma, the sampling interval is so sparse that the correlation with BDP-98 is not good.

Fig. 14 shows the result of the spectral analysis (FFT) on susceptibility record for BDP-96-2 and BDP-98 (Horii et al., 2001a; Sakai et al., 2003). The time scale that is based on magnetostratigraphy and adjusted using correlation of change in physical properties with insolation curve at latitude 65° N was used (Kashiwaya et al., 1998). Magnetic susceptibility data that is divided into 500kyr segments was analyzed. Analyses for period of 1.7-0.6 Ma from BDP-98-1 (a), 3.4-2.3 Ma from BDP-98 (b) and 1.7-0.6 Ma from BDP-96 (c) shows that there are orbital periodicities (Milankovitch cycle) of eccentricity (400kyr and 100 kyr), obliquity (41kyr) and precession (23 kyr) in the climate around Lake Baikal. It suggest that climate around Lake Baikal reflect global paleoclimatic change. Another precession cycle, periodicity of 19 kyr is not clear because of limitation of analytical methods and sampling interval.

Predominant period transit from 100 kyr during 3.4-3 Ma to 41 kyr after 3Ma. This transition of predominant period can be related with the elevation of Himalaya and Rocky mountains (Masuda, 1991) and formation of Panama land bridge (Driscoll and Haug, 1998). Again, Fig. 14 shows also predominance of 100 kyr periodicity after 1.2 Ma. This transition can be related to the elevation of Himalayan Mountains and Tibetan Plateau (Yasunari et al., 1991) .

In the climatic record from Baikal showed pronounced 23-kyr precession cycle compared to paleocliamtic records on marine sediments. This characteristic is, therefore, considered to be local climatic feature around Lake Baikal region. It may suggest that in an inland region at high latitude like Lake Baikal area, the climatic change is sensitive to changes in insolation (Horii et al., 2001a).

5-3. Sediment cores from other area

In the cores on the site out of Academician ridge, no distinct normal-reverse polarity pattern of magnetiztion is obtained. Here, the knowledge on the cores obtained from studies on BDP at present is introduced.

The Buguldeika site in which drilled BDP-93 cores(52°30'53"N, 106°9'10"E; core length 100 m), lies on the western margin between the central and southern basin, offshore of the Buguldeika River and directly across from the Selenga delta. As this area is supplied sediment from Selenga delta, the sedimentation rate is quite high; average sedimentation rate in Holocene is 0.15 mm / yr (Colman et al., 1993). Lithology of BDP-93 cores changes on 40-50 m. The lower sequence (< 40 m) is coarser grained with abundant turbidites, and the upper sequence is formed of a diatom-rich fine-grained silt-clay sediment with laminae. At this depth, sonic velocity, density, grain size and magnetic properties of sediments also change. It suggest that the environmental change occurred at the time (BDP-93 Baikal Drilling Project members, 1995).

The paleomagnetic records for 100 m long cores (BDP-93-1,2) from Buguldeika saddle show dominant normal inclination, and thus the sedimentary sequence is entirely Brunhes Chron (780 ka BP～) in age. Some magnetic excursions in Brunhes Chron are detected in the both cores at depth of 20 m, 26 m, 70 m and 80 m. Referring to the time scale based on carbon isotope age and added effect of compacting (Kashiwaya et al., 1997), the gases of magnetic excursion found in the cores are estimated 100 kyr, 12 kyr, 31 kyr and 34 kyr respectively. Horii et al. (2001b) suggest these ages of magnetic excursions from the cores are concordant with some of recently assembled magnetic excursions (Lund et al., 1998; Langreis et al., 1997).

Drilling site of BDP-97(51°'N, 105°'E; core length 42 m) located at central of southern basin of Lake Baikal, the water depth on the site is quite deep (1400 m) and the sedimentation rate is high. The most thick turbidite layer over 4.2 m was found in the core. Upper 8m of the core, two shallow inclinations were detected, however their estimated ages of the inclinations are not correlate with the ages of known magnetic excursion. These shallow inclinations could be affected from the turbidite.

In BDP-99 (51°51'02"N, 105°32'49"E; core length 300 m) core from southern basin, the consecution of reversed inclination was founded. This core can include Matuyama reversed Chron. Therefore, the sedimentation rate in the site BDP-99 may be lower than those at BDP-93 and BDP-97.

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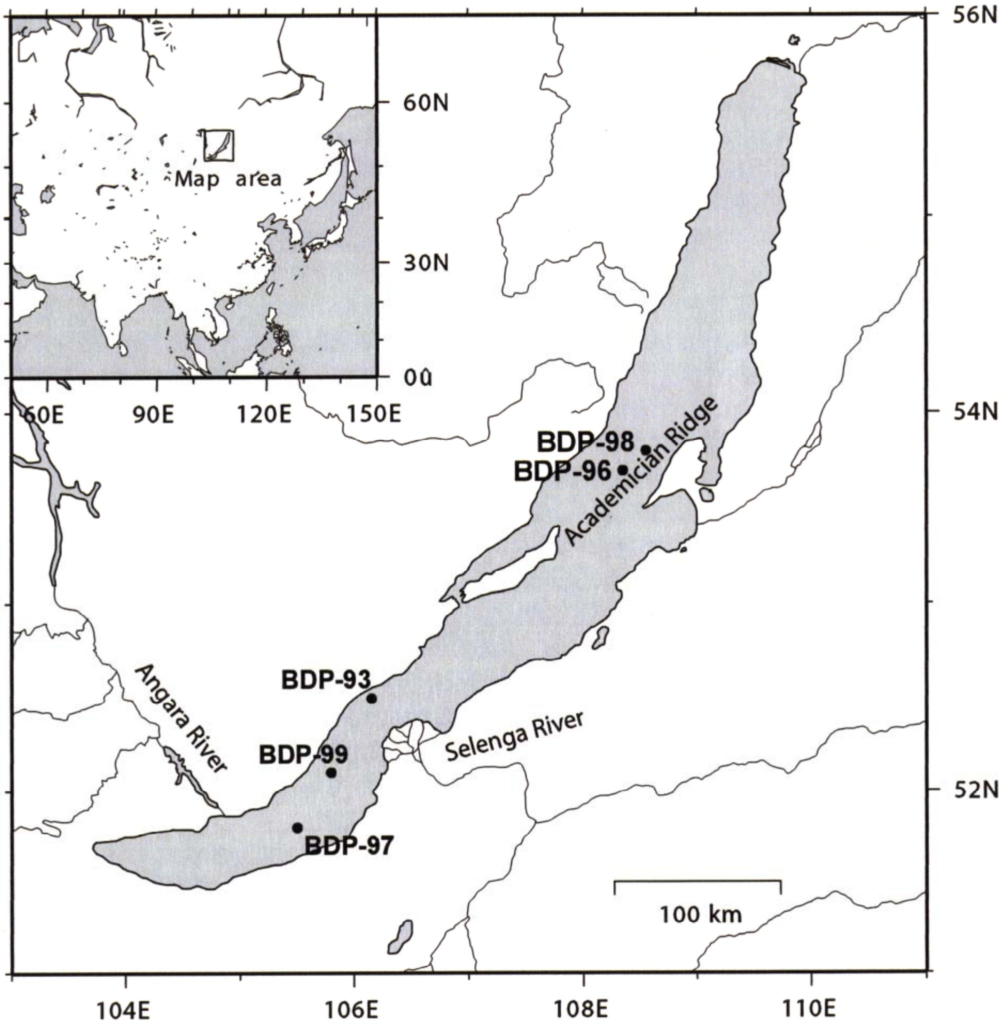
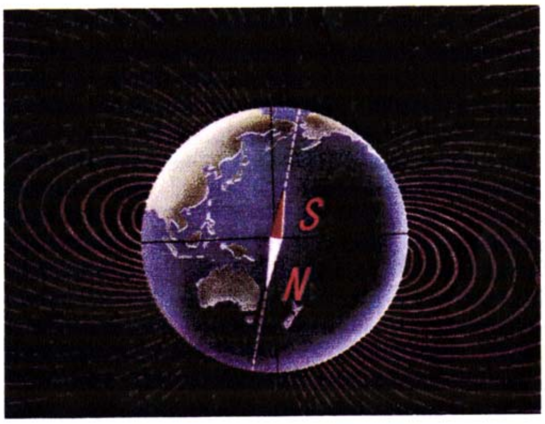
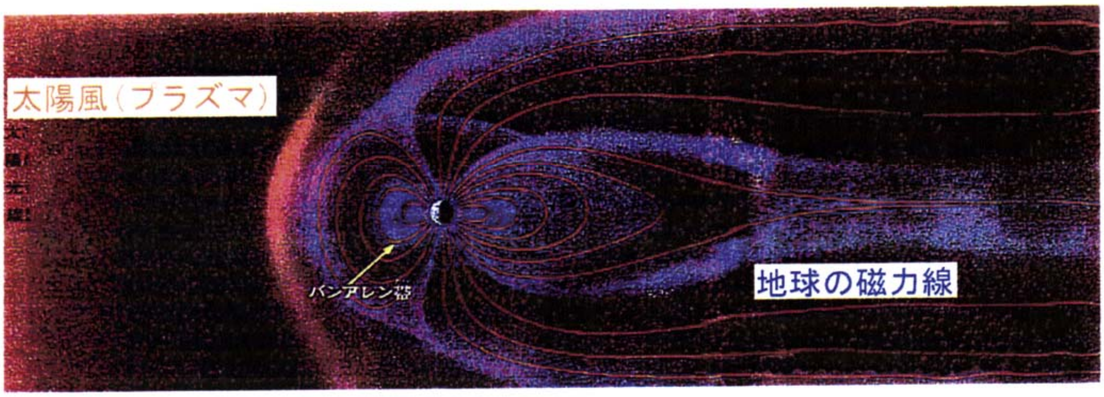


コア名	掘削地点	水深	コア長
BDP-93	ブグルジェイカ鞍部	332m	100m
BDP-96	アカデミシャン湖嶺	321m	200m
BDP-97	南湖盆	1436m	42m
BDP-98	アカデミシャン湖嶺	337m	600m
BDP-99	ポソルスカヤバンク	201m	300m

Figure 1 Sampling localities at Lake Baikal.

地球の磁石　地球磁場　太陽プラズマ





地球の磁力線は地球を守っている

Figure 2 Geomagnetic field

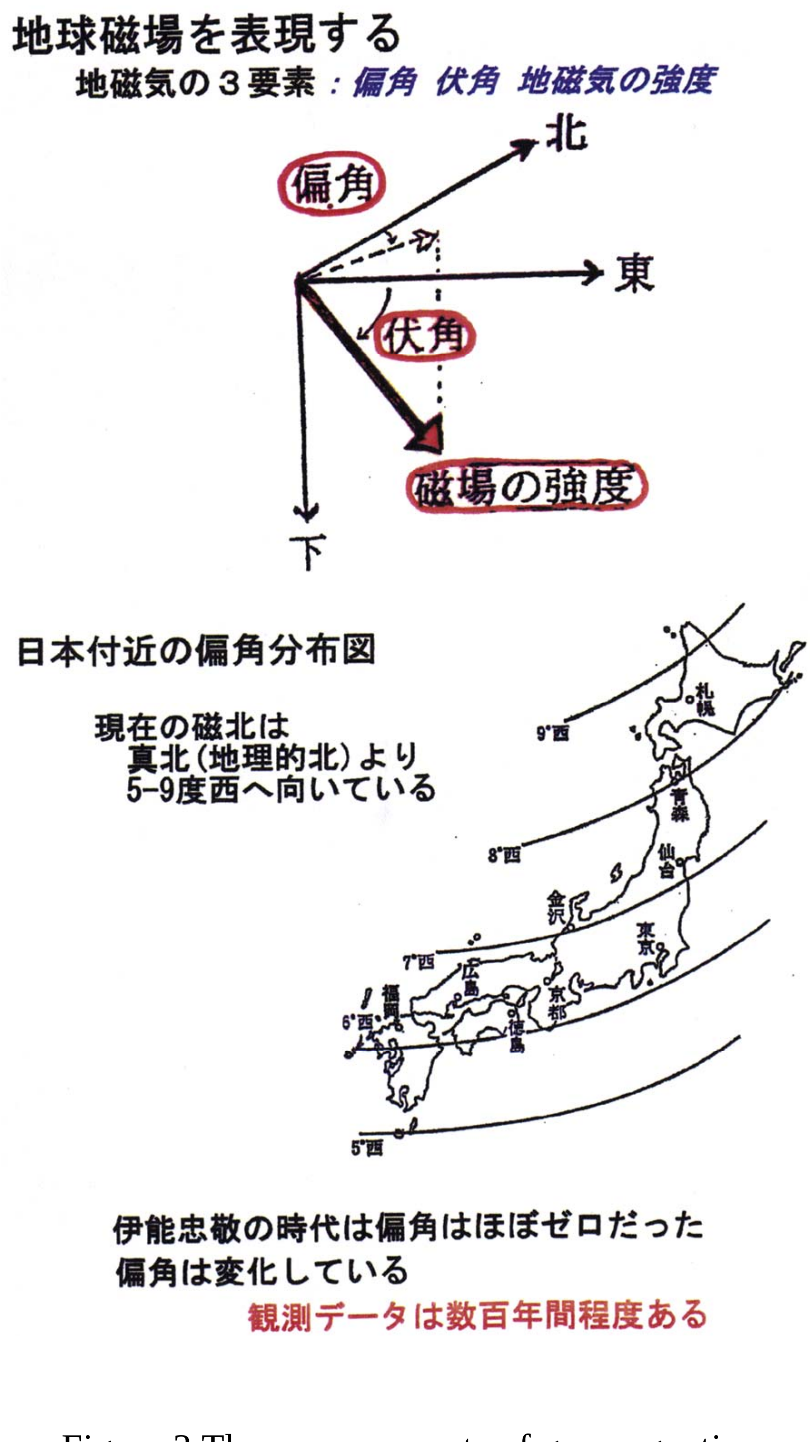


Figure 3 Three components of geomagnetism

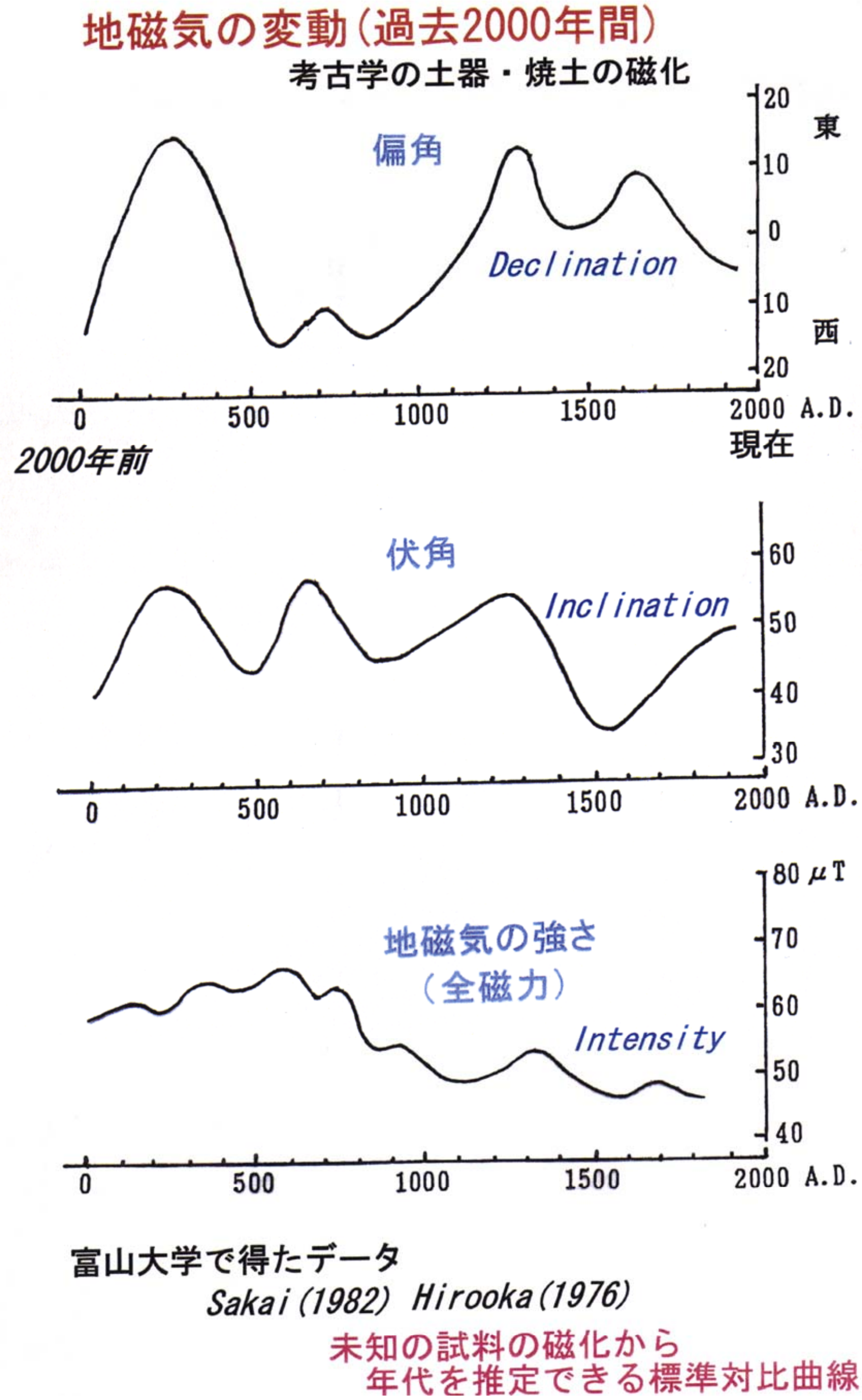


Figure 4 Changes in geomagnetic properties at Japan over the past 2000 years. Data of amplitude and magnetic inclination were obtained from Hirooka (1971), data of total magnetic force were from Sakai and Hirooka (1986).

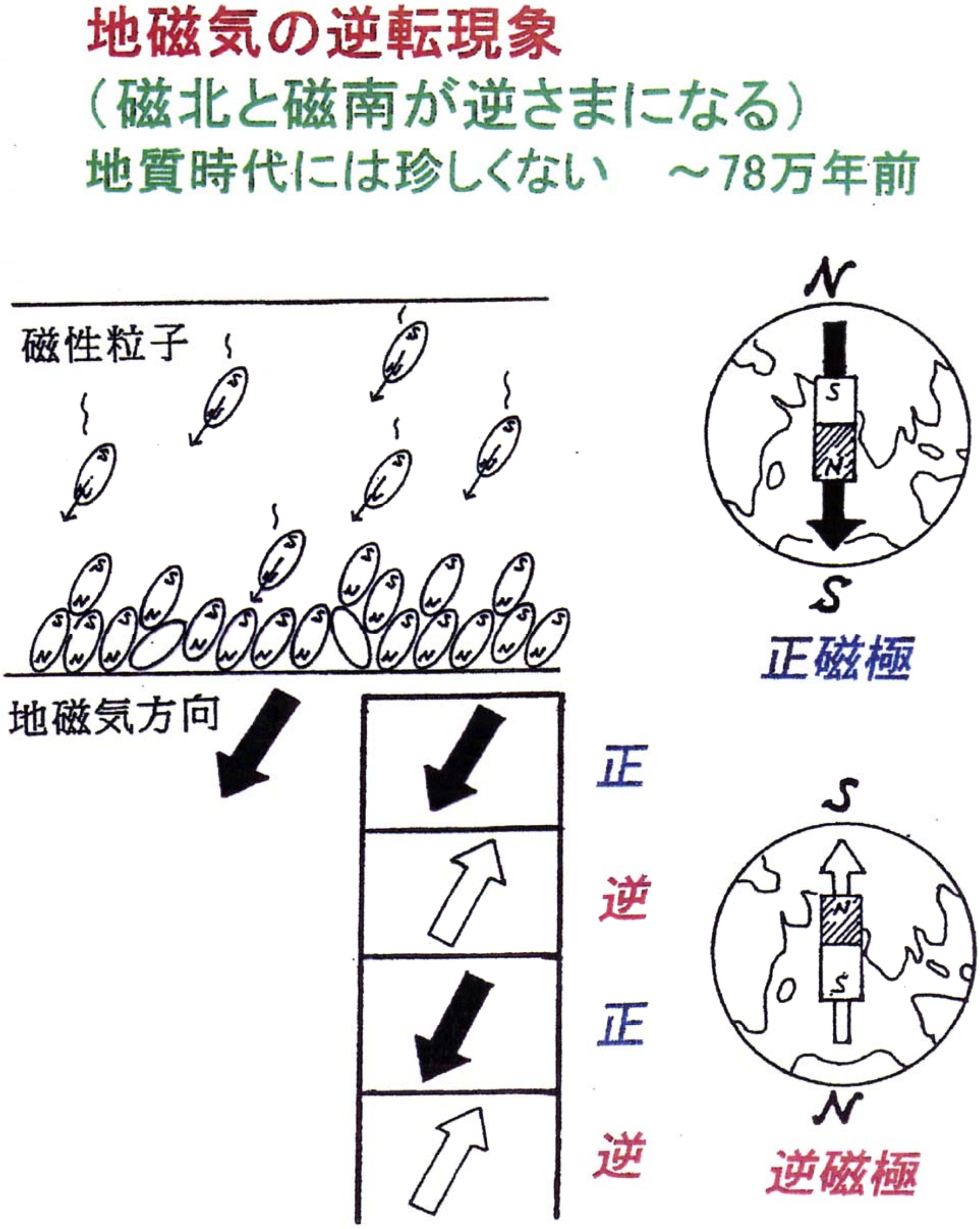
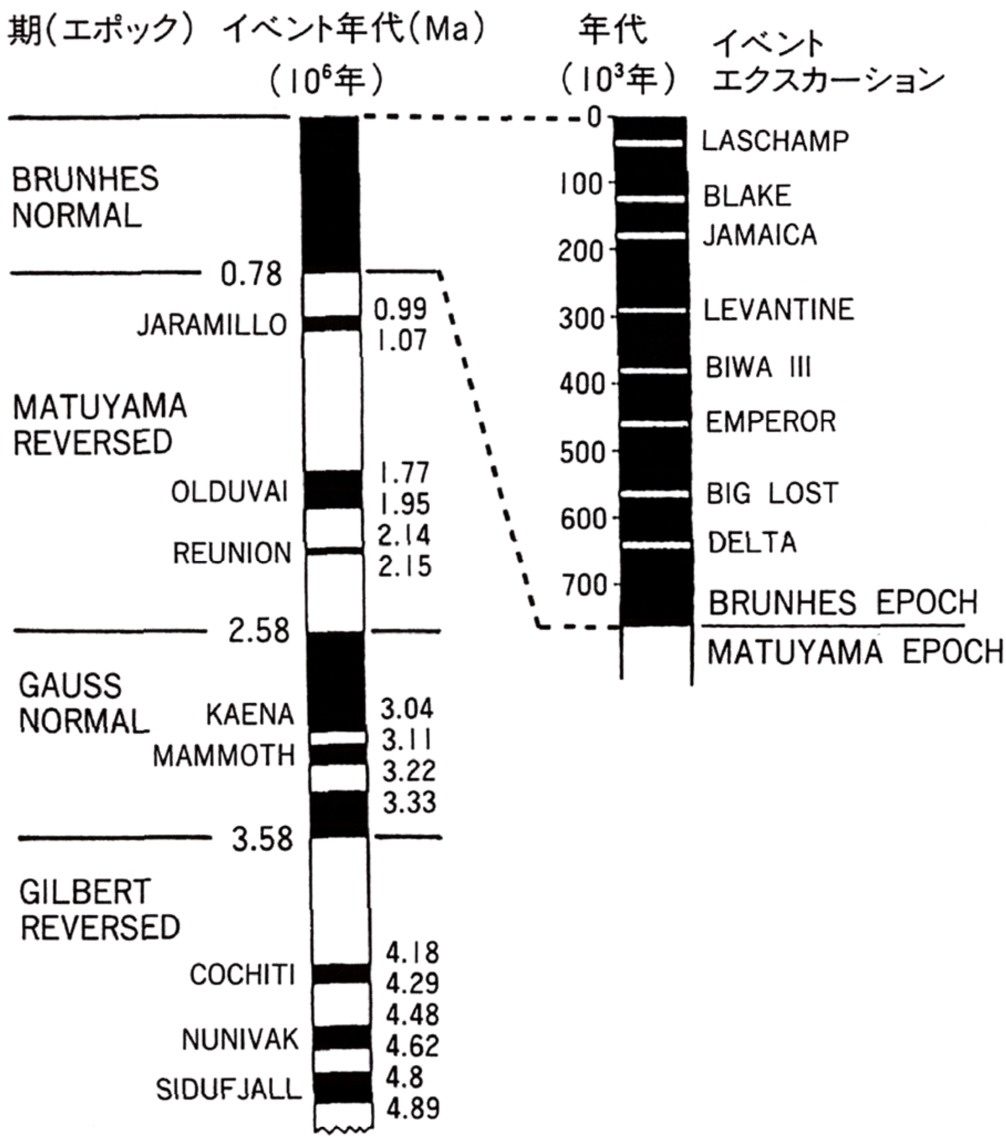
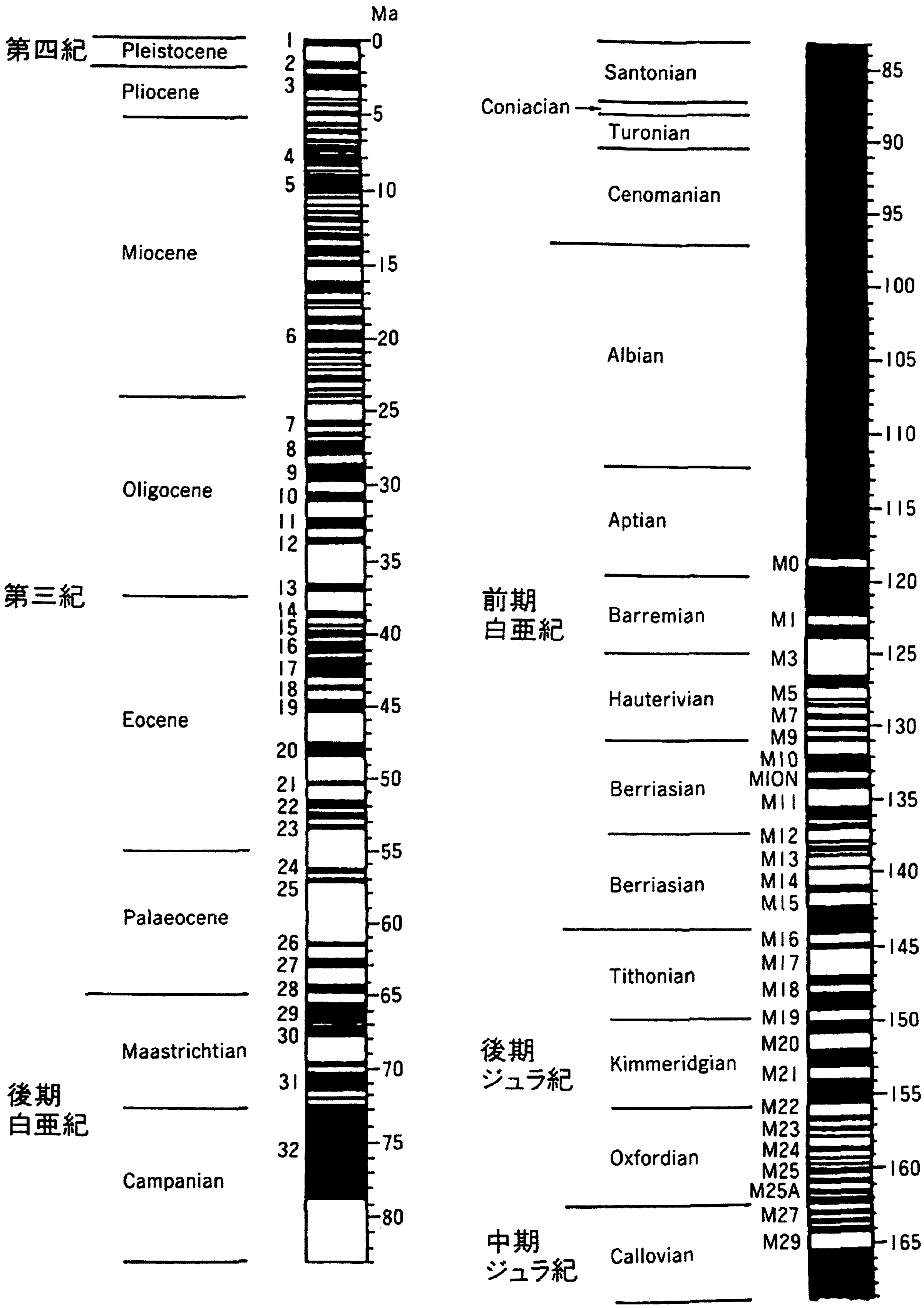


Figure 5 Reversion of geomagnetism and sedimentary residual magnetization.



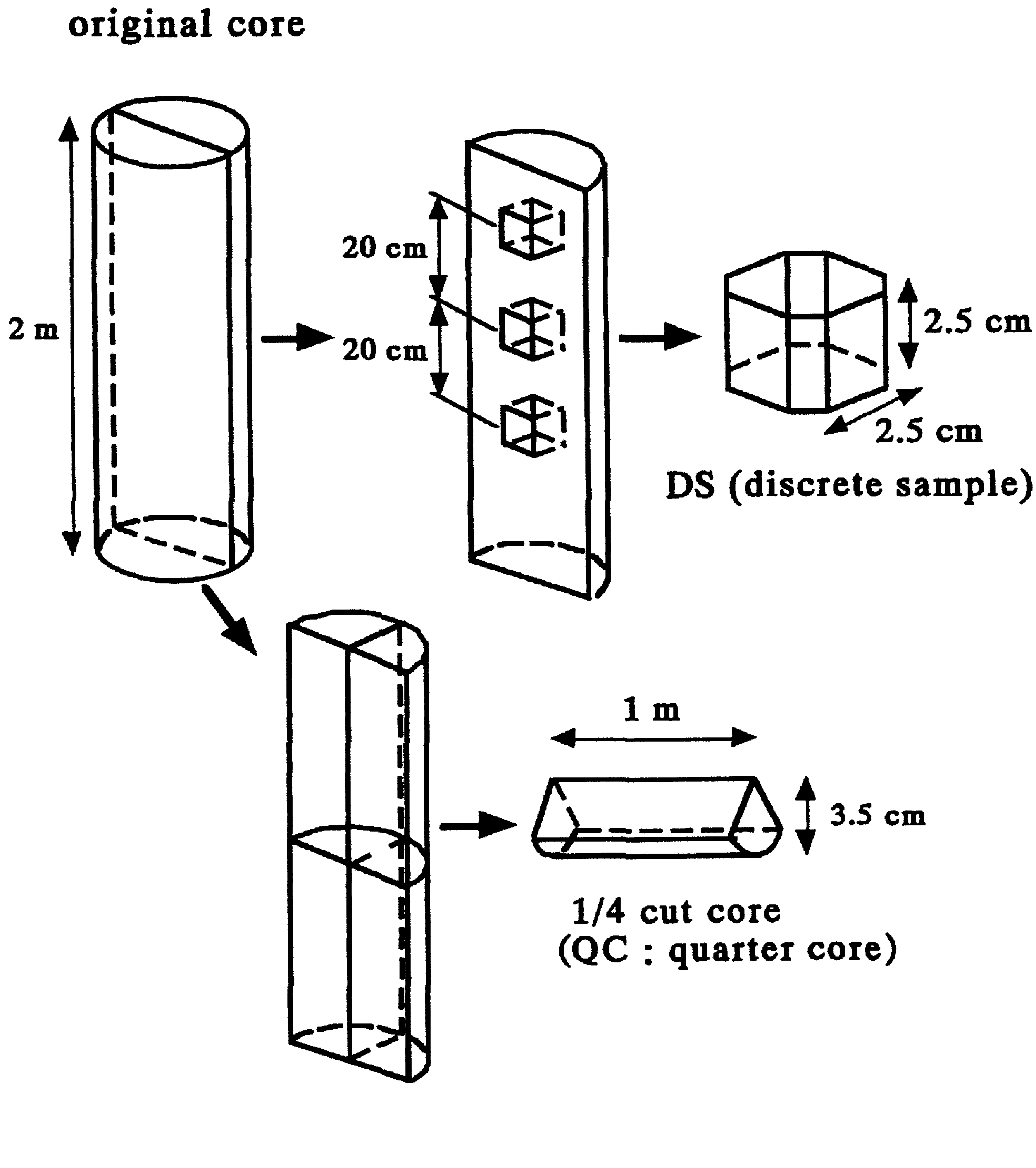
過去 **500** 万年間の地磁気逆転（Cande and Kent, 1995）と右には地磁気エクスカーション（Champion *et al*., 1988）を示す

Figure 6a Chronological table of reversion in geomagnetism.



Cox（1982）による 1 億 7000 万年間の磁極逆転タイムスケール

Figure 6b Chronological table of reversion in geomagnetism.



Discrete samples and quarter-core samples were collected from the half lengthwise core for the paleomagnetic study.

Figure 7 Sampling methods from half cores.

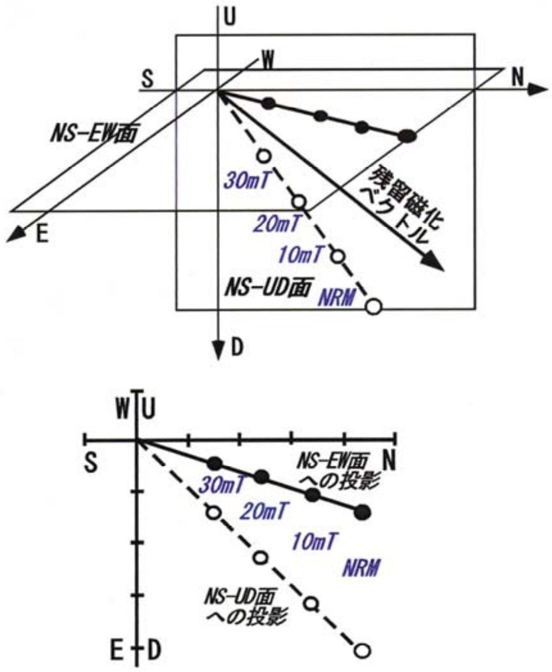


Figure 8 Seider-Belt Diagram.

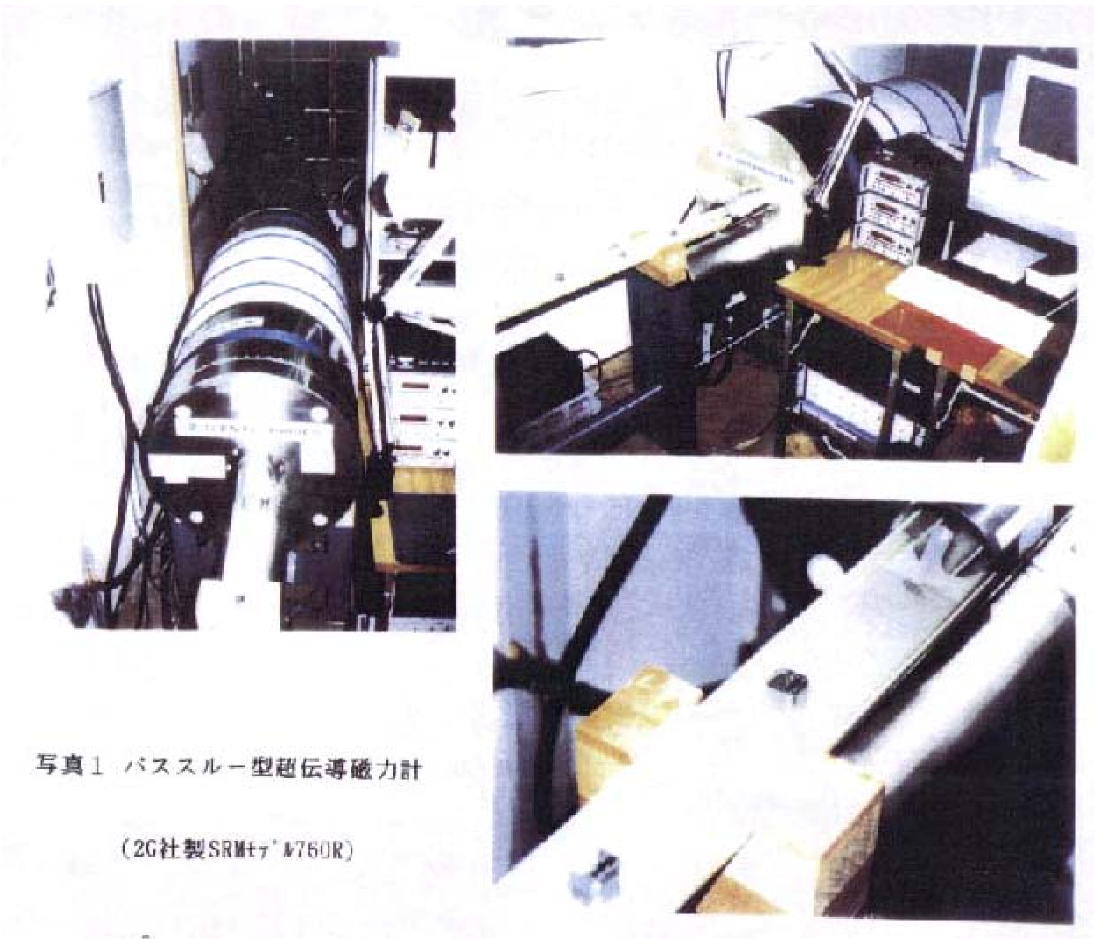


Figure 9 Path-through type magnetometer (SQUID).

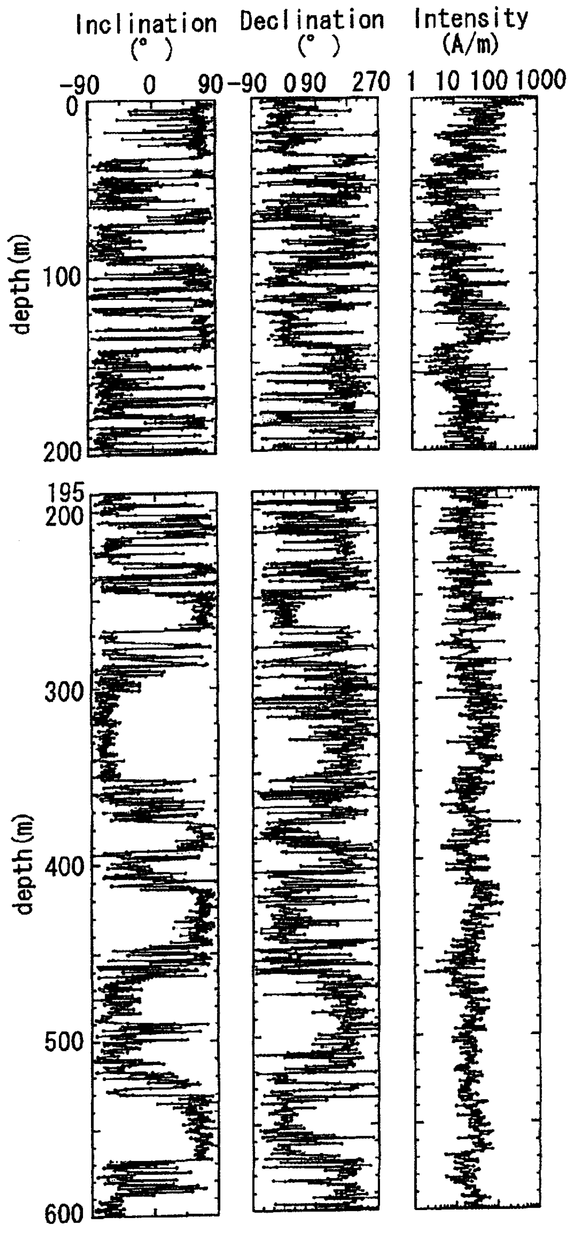


Figure 10 Changes in amplitude and magnetic inclination and total magnetic force

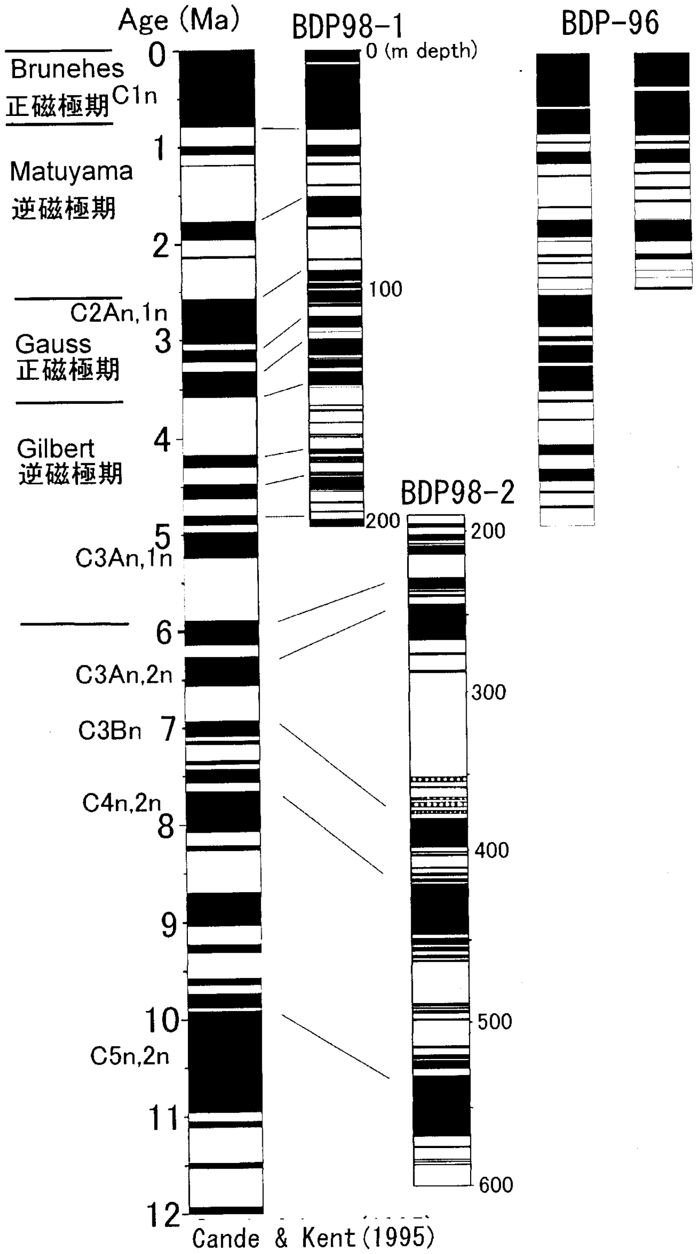


Figure 11 Comparison between positive-negative patterns and chlonorogical reversion table from BDP-96, BDP-98 samples.

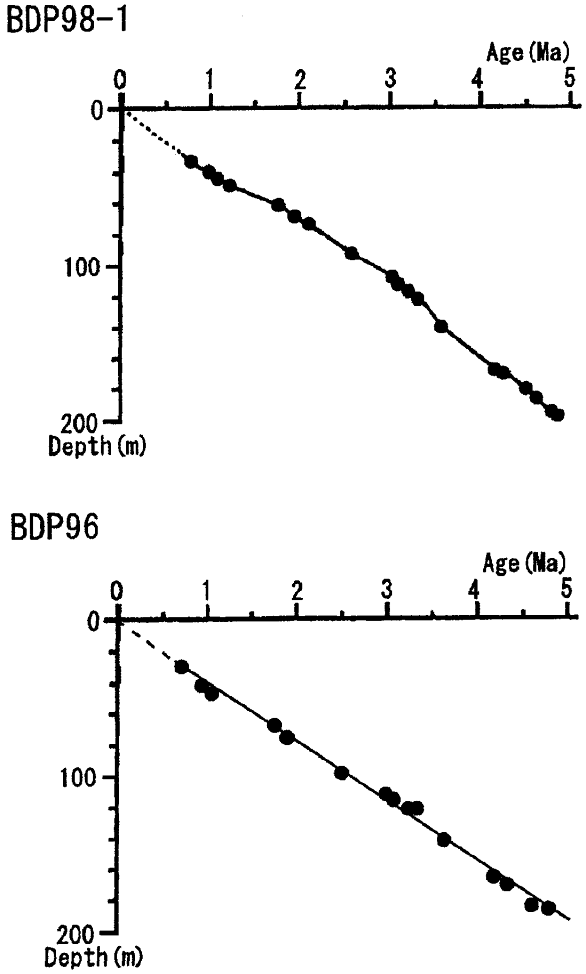


Figure 12 Relationship between depth and age from BDP-96-1and BDP-98-1 samples.

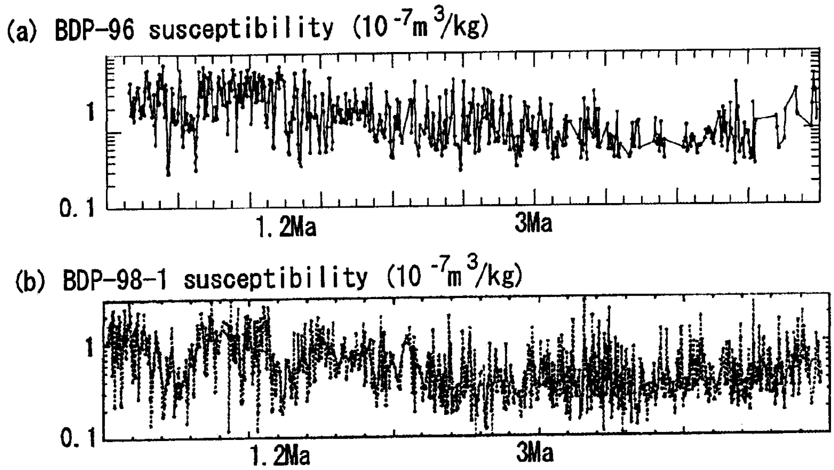


Figure 13 Changes in magnetic susceptibility

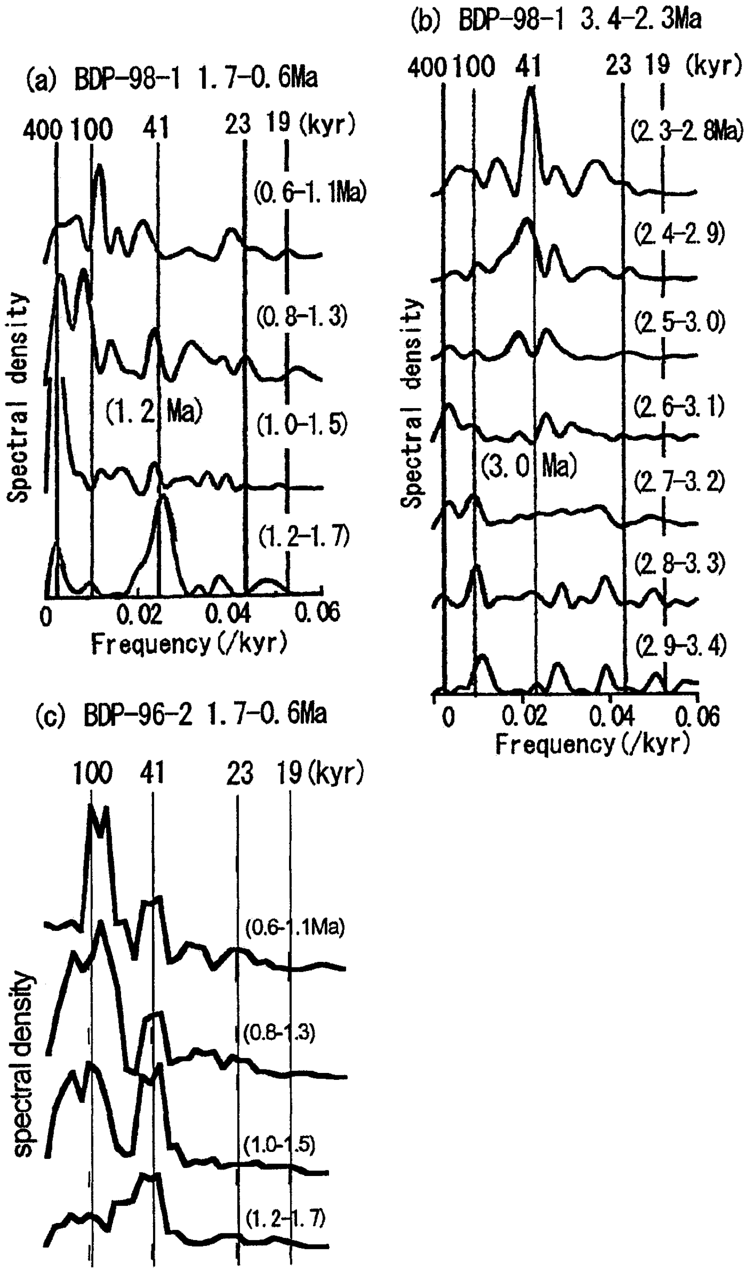


Figure 14 Results of spectrum analysis. (a)BDP-98-1 の 1.7-0.6Ma, (b)BDP-98 の 3.4-2.3Ma, (c)BDP-96 の 1.7-0.6Ma.